Tsunami early warning using earthquake rupture duration

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Effective tsunami early warning for coastlines near a tsunamigenic earthquake requires notification within 5-15 minutes. We have shown recently that tsunamigenic earthquakes have an apparent rupture duration, T_0, greater than about 50 s. Here we show that T_0 gives more information on tsunami importance than moment magnitude, M_w, and we introduce a procedure using seismograms recorded near an earthquake to rapidly determine if T_0 is likely to exceed T=50 or 100 s. We show that this "duration-exceedance" procedure can be completed within 3-10 min after the earthquake occurs, depending on station density, and that it correctly identifies most recent earthquakes which produced large or devastating tsunamis. This identification forms a complement to initial estimates of the location, depth and magnitude of an earthquake to improve the reliability of tsunami early warning, and, in some cases, may make possible such warning.

Introduction

Effective tsunami early warning for coastlines near a tsunamigenic earthquake requires notification within 5-15 minutes after the earthquake origin time (OT). Organizations such as the Japan Meteorological Agency (JMA), the German-Indonesian tsunami early warning system (GITEWS) and the West Coast and Alaska (WCATWC), and Pacific (PTWC) Tsunami Warning Centers first identify potentially tsunamigenic earthquakes based on rapidly determined earthquake parameters such as location, depth and magnitude. JMA issues warnings for Japan about 3 min after OT for events expected to produce a tsunami with height exceeding 0.5 m. GITEWS issues warnings for Indonesia within 5 min after OT based on the earthquake parameters and corresponding, pre-calculated tsunami scenarios. WCATWC and PTWC issue regional warning notifications within about 5-10 min after OT for shallow, underwater events around North America and in the Pacific basin with moment magnitude $M_w \geq 7.5$ [e.g., *Hirshorn et al.*, 2009].

Recently, through analysis of teleseismic, *P*-wave seismograms (30°-90° great-circle distance; GCD), we have shown that an apparent rupture duration, T_0, greater than about 50 s forms a reliable indicator for tsunamigenic earthquakes [*Lomax and Michelini*, 2009; *LM2009* hereinafter]. Here we exploit this result and introduce a "duration-exceedance" procedure to rapidly determine if T_0 for an earthquake is likely to exceed 50 or 100 s and thus to be a potentially tsunamigenic earthquake. This procedure does not require accurate knowledge of the earthquake location or magnitude and can be completed within 5-10 min after OT for most regions in the world.

Tsunami importance, moment magnitude and rupture duration

We consider a reference set of 76 underwater earthquakes since 1992 with $M_w \geq 6.6$ (Table S1). Since there is currently no uniform, physical measure of size available for most tsunamis, following *LM2009*, we define an approximate measure of tsunami importance, I_t, based on 0-

4 descriptive indices, i, of tsunami effects (deaths, injuries, damage, houses destroyed), and maximum water height h in meters from the NOAA/WDC Historical Tsunami Database (http://www.ngdc.noaa.gov/hazard/tsu_db.shtml): $I_t = i_{height} + i_{deaths} + i_{injuries} + i_{damage} + i_{houses\text{-}destroyed}$, where i_{height}=4,3,2,1,0 for $h \geq 10$, 3, 0.5 m, $h>0$ m, $h=0$ m respectively. We set $I_t=0$ for events not in the database, and note that I_t is approximate and unstable since it depends strongly on the available instrumentation, coastal bathymetry and population density in the event region. $I_t \geq 2$ corresponds approximately to the JMA threshold for issuing a "Tsunami Warning"; the largest or most devastating tsunamis typically have $I_t \geq 10$.

Figure 1 shows a comparison of I_t with the Global Centroid-Moment Tensor (CMT) moment-magnitude, M_w^{CMT} [*Dziewonski et al.*, 1981; *Ekström et al.*, 2005], and with T_0 durations calculated from high-frequency, *P*-wave seismograms at teleseismic distance following the procedure of *LM2009*. The thresholds $M_w^{CMT} \geq 7.5$ and $T_0 \geq 50$ s both identify most of the events with $I_t \geq 2$ (see also Tables 1 and S1). M_w^{CMT}, however, shows no clear relationship to I_t or to event type; in contrast, T_0 tends to increase for larger I_t, especially for tsunami earthquakes (type T; characterized by unusually large tsunamis and a deficiency in moment release at high frequencies, *e.g.*, *Satake* [2002]). We do not consider here the energy-to-moment parameter, Θ, which is useful for identification of tsunami earthquakes [*Newman and Okal*, 1998], because it is not a good indicator for tsunamigenic events in general [*e.g.*, *LM2009*].

Since CMT-based M_w magnitudes are only available 30 min or later after OT, rapid magnitude estimates such as M_{wp} [*Tsuboi et al.*, 1995; *Tsuboi et al.*, 1999] are used for tsunami warning. But M_{wp} performs poorly relative to M_w^{CMT} or T_0 for identifying events with $I_t \geq 2$ (Table 1). Other rapid magnitude estimates for large earthquakes [e.g., *Hara*, 2007; M_{wpd}, *LM2009*; m_{Bc}, *Bormann and Saul*, 2009] may perform nearly as well as M_w^{CMT} or T_0 (e.g., M_{wpd} in Tables 1 and S1), but are not available until about 15 min or later after OT. Thus very rapid determination of a large T_0, e.g. $T_0 \geq 50$ s, would provide important complementary information to initial location, depth and magnitude estimates for early assessment of earthquake tsunamigenic potential.

Methodology for rapid rupture duration determination

We determine if T_0 for an earthquake is likely to exceed pre-determined thresholds T=50, 100 s through high-frequency (HF) analysis of vertical-component, broadband seismograms [*e.g.*, *Lomax*, 2005; *Lomax and Michelini*, 2005; *Lomax et al.*, 2007; *LM2009*]. We proceed as follows for each seismogram (Figure 2): 1) apply a 4-pole, 1-5 Hz Butterworth band-pass filter to form a HF trace; 2) auto-pick the *P* arrival time on the HF trace; 3) measure A_{ref}, the *rms* amplitude for the first 25 s after the *P* time on the HF trace; 4) calculate the ratio of the *rms* HF amplitude from 50-60 s after the *P* time with A_{ref} to obtain a station duration-exceedance level for 50 s, l_{50}, and a similar ratio for 100-120 s after *P* with A_{ref} to obtain l_{100}.

We define event duration-exceedance levels, L_T, T=50, 100 s, as the median (50 percentile) of the station l_{50}, l_{100} values after removing the upper 10 percentile of values to avoid noisy or anomalously long HF signals. If an event exceedance level L_T is greater (less) than 1.0, then T_0 is likely (unlikely) to exceed T seconds. This procedure does not require an event location or magnitude, and all processing can be performed in the time domain; indeed, individual station l_{50} and l_{100} values can be calculated autonomously at each station.

Application to reference earthquakes

We apply the duration-exceedance procedure to the reference earthquakes using data up to 10 min after OT from stations at 0-30° GCD from each event to simulate the information available in the first minutes after an earthquake occurs. The L_{50} exceedance level results are tabulated in Table 1 and all event parameters and exceedance level results in Table S1; plots of the time evolution of the L_{50} calculation for two events are shown in Figure 3, and for L_{50} and L_{100} for selected events in Figure S1 in the supplement.

A comparison of L_T, T=50, 100 s, with the T_0 durations calculated from teleseismic observations (Figure 4a; Table S1) shows that, in general, the duration-exceedance level L_T increases with increasing T_0 and is greater than 1 for events with $T_0>T$. There is much scatter in these results, due primarily to the difficulty in determining cutoff points on the HF seismograms (e.g., Figure 2; *LM2009*), but they confirm that the rapidly available L_T measures form reliable proxies for the teleseismic, T_0 durations.

Discussion

A comparison of the L_{50} exceedance level with tsunami importance, I_t, (Figure 4b; Tables 1 and S1) shows correct identification ($L_{50}\geq1$) of most events with $I_t\geq2$. The miss-identified events are a shallow, offshore thrust event, I_t=8, 2003.05.21, M_w6.8, N Algeria, and two shallow, oceanic, strike-slip events, I_t=13, 1994.11.14, M_w7.1, Philippines and I_t=9, 2006.03.14, M_w6.7, Seram Indonesia. All of these events are also missed using the magnitude discriminant, $M_w\geq7.5$, and thus produced larger than expected tsunamis. There are 13 events with $I_t<2$ that are falsely identified by $L_{50}\geq1$ values as likely tsunamigenic ($I_t\geq2$); 7 of these events have I_t=1 and thus produced small tsunamis, while some may have involved under land or strike-slip rupture, or produced unobserved tsunamis. The remaining events with $I_t<2$ are correctly identified as unlikely tsunamigenic by $L_{50}<1$ values. For most events, the L_{50} values have stabilized within 4-6 min after OT (Figures 3 and S1).

The L_{50} discriminant correctly identifies 90% of tsunamigenic events with $I_t\geq2$. The overall performance of the L_{50} discriminant is similar to that of M_w^{CMT}, M_{wpd}, and teleseismic T_0 (Table 1), though these latter three measures are not available until at least 30, 15 and 15 min, respectively, after OT [*LM2009*]. In contrast, the rapidly available M_{wp} discriminant correctly identifies only 52% of tsunamigenic events with $I_t\geq2$, primarily because M_{wp} underestimates the size of events with M_w^{CMT}>7.0-7.5, particularly tsunami earthquakes and other events with long rupture duration [*e.g.*, *LM2009*].

The results for L_{100} (Figure 4; Table S1) show that $L_{100}\geq1$ identifies well events with longer duration, T_0, events with $I_t\geq10$, and most tsunami earthquakes (type T). In contrast, 1994.11.14 Philippines, 1998.07.17 Papua New Guinea, and two intraplate events (type P) with only moderately long T_0 but large I_t have $L_{100}<1$ values. For events in regions with denser station coverage, the L_{100} values have stabilized by 6-8 min after OT (Figure S1).

Since the station l_T exceedance values can be calculated autonomously at each station, they could aid in providing very early, local tsunami warning. For example, the first station l_{50} values for the 2006 Indonesian event in Figure 3 are available only 2-4 min after OT. Single l_T exceedance values must be used with care, however, as they can be biased at small epicentral distances by HF radiation effects and secondary phases, especially *S*.

Conclusions

We have shown that apparent rupture duration, T_0, provides more information on tsunami importance, I_t, than does moment magnitude and that earthquakes with a high tsunamigenic potential (e.g., possible tsunami importance $I_t\geq2$ or $I_t\geq10$) can be rapidly and reliably identified through a procedure that determines if T_0 is likely to exceed 50 or 100 s. This identification can be performed within 5-10 min after OT for most regions using currently available seismographic stations, and probably in less than 3-5 min for regions with higher station density, such as Japan, Taiwan, Indonesia, the Mediterranean and Western North America. This identification forms a complement to initial estimates of the location, depth and magnitude of an earthquake to improve the reliability of tsunami early warning, and, in some cases, may make possible such warning.

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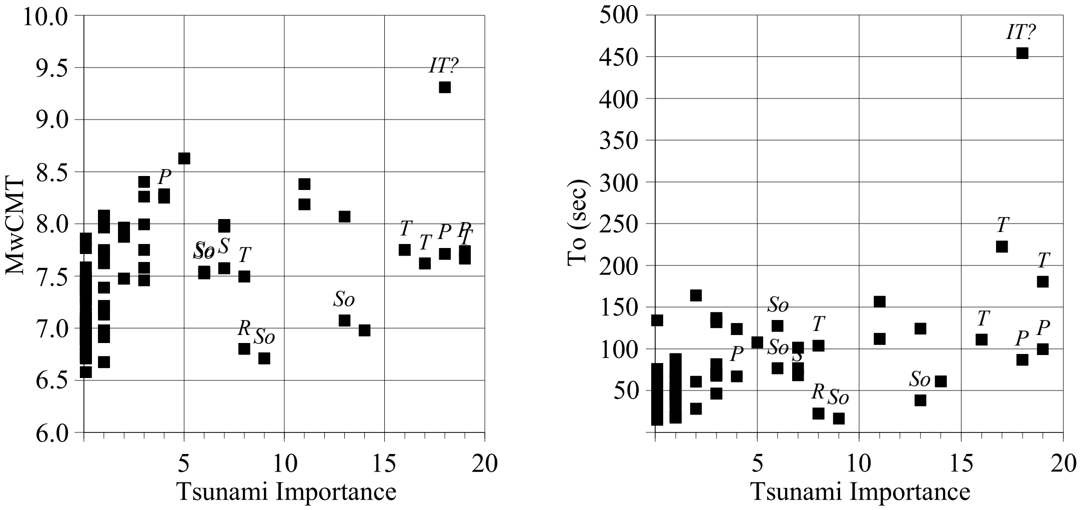
Table 1 – Results for L_{50} classification* of tsunamigenic earthquakes

Discriminant	Available (min after OT)	Critical Value	Correctly Identified			Missed	False
			$I_t \geq 2$	%**	$I_t < 2$	$I_t \geq 2$	$I_t < 2$
M_w^{CMT}	30+	7.5	27	87%	34	4	11
T_0 (teleseismic)	15+	50	26	84%	32	5	13
M_{wpd} (raw)	15+	7.5	24	77%	33	7	12
M_{wp}	3-10	7.5	16	52%	38	15	7
L_{50}	3-10	1.0	28	90%	32	3	13

* 76 events classified; 31 have $I_t \geq 2$

** percent of all events with $I_t \geq 2$ that are correctly identified



a) b)

Figure 1

Comparison of tsunami importance I_t with (a) moment-magnitude M_w^{CMT} and (b) with apparent source duration, T_0, calculated from teleseismic observations. Event labels show event type for non interplate-thrust events with $I_t \geq 2$ (*T*–tsunami earthquake; *P*–intraplate; *So*–strike-slip oceanic, *S*–strike-slip continental, *R*–reverse-faulting).

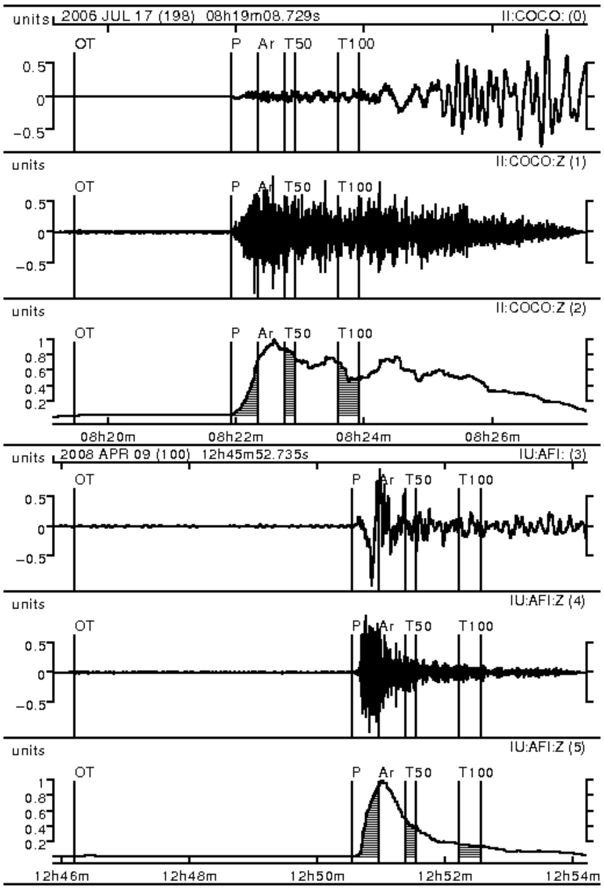


Figure 2

Raw, broadband velocity seismogram, HF seismogram and smoothed *rms* amplitude of HF seismogram for two events: (upper 3 traces) 2006.07.17, M_w7.7, T_0=180 s, I_t=18, Indonesia tsunami earthquake recorded at station COCO at 11º GCD, and (lower 3 traces) 2008.04.09, M_w7.0, T_0=23 s, I_t=0, Loyalty Islands interplate thrust recorded at station AFI at 19º GCD. OT – origin time; P – automatic *P* pick; P to Ar, T50 and T100 – time windows (shaded) for calculation of *rms* HF amplitude for A_{ref}, l_{50} and l_{100}, respectively.

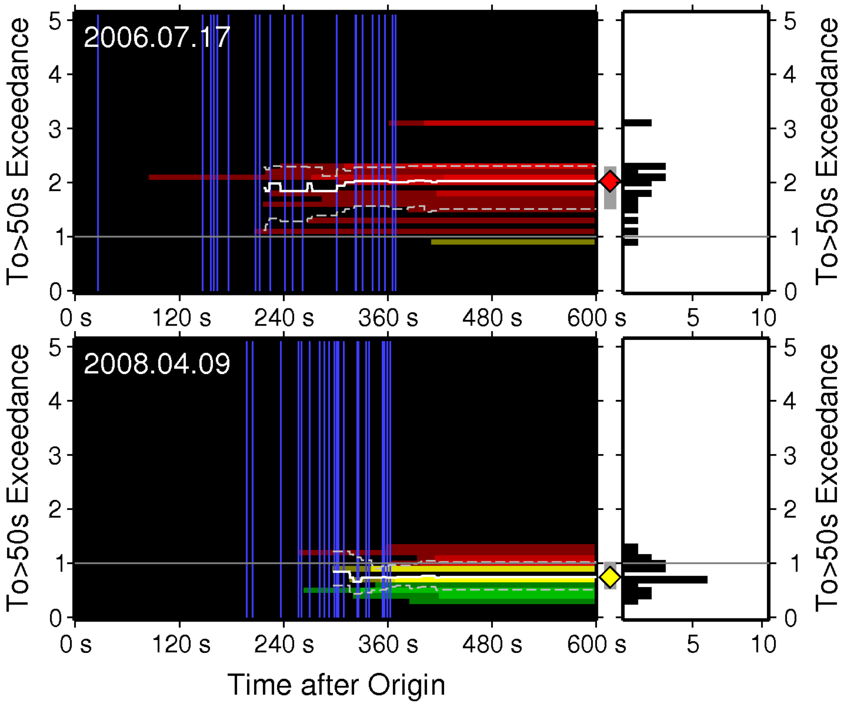
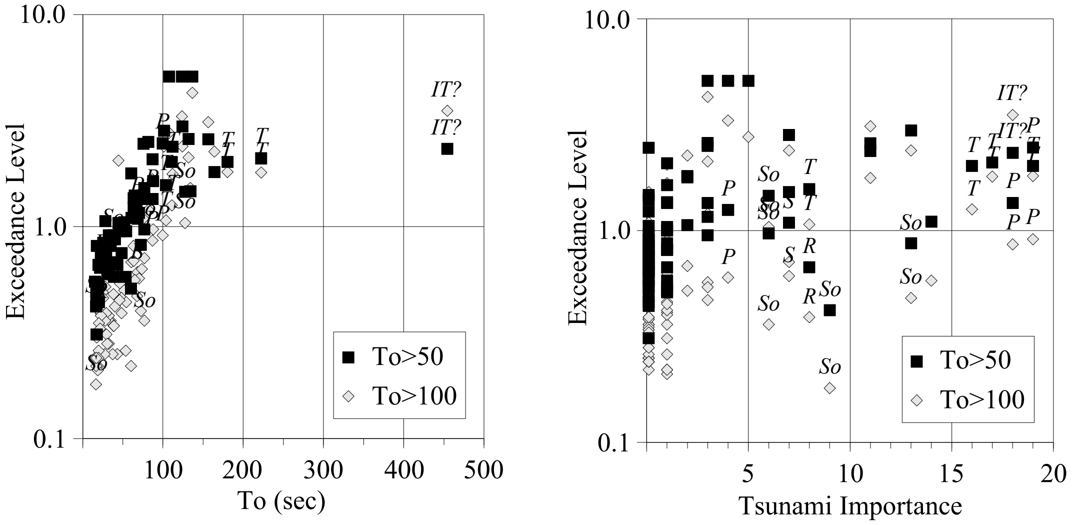


Figure 3

Evolution for 10 min after OT of the T_0>50 s exceedance level (L_{50}) calculation for: (upper) 2006.07.17, M_w7.7, T_0=180 s, I_t=18, Indonesia tsunami earthquake, and (lower) 2008.04.09, M_w7.0, T_0=23 s, I_t=0, Loyalty Islands interplate thrust. Blue lines show *P*-arrival times for each station; red, yellow or green horizontal bars show the station exceedance levels, l_{50}, starting at its first reported time (about 60 s after the corresponding *P* time). Histogram shows l_{50} values at 600s; the median (50 percentile) and bounds (20 and 80 percentile), respectively, for L_{50} are indicated by solid and dotted white lines on the main plot and as a colored diamond and error bar. Red indicates l_{50}(or L_{50})≥1 (likely that T_0>50 s and I_t≥2); yellow indicates 0.7≤l_{50}(or L_{50})<1 (possible that T_0>50 s and I_t≥2); green indicates l_{50}(or L_{50})≤0.7 (unlikely that T_0>50 s or I_t≥2). For both events the L_{50} values have stabilized by 4-6 min after OT. For real-time monitoring, comprehensive information about exceedance level could be provided by a time-sliding display similar to the above.



a) b)

Figure 4

Comparison of exceedance levels L_{50} and L_{100} with (a) apparent source duration T_0 calculated from teleseismic observations and (b) tsunami importance I_t. Event type labels as in Figure 1.